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Completion Report

A Geological Approach to Characterizing Aquifer Heterogeneity

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Objectives

Spatial variations of hydraulic conductivity have generally been recognized as the dominant medium-dependent control on the transport and dispersion of contaminants in groundwater. Mathematical models that use statistical descriptions of the hydraulic conductivity spatial distribution are available to predict contaminant transport. Such models are expected to be major tools in dealing with contamination problems at DOE sites. Unfortunately, the statistical parameters needed for such models can usually only be obtained through geostatistical analysis of very large numbers of hydraulic conductivity measurements, with associated large costs and often-significant human risk at highly contaminated sites.

More accurate and realistic conceptual models for the actual distribution of hydraulic conductivity, requiring fewer field data, would increase the reliability of contaminant transport predictions while decreasing their cost. The objectives of our project can therefore be summarized in the following question: "How can the data requirements for geostatistical analysis of hydraulic parameters be reduced by incorporation of geological expertise and macroscopic proxy information into new mathematical models?" Specifically, we proposed to combine intensive geological field observations with permeability measurements to discover relationships between sediment depositional processes, geological structures, and the geostatistics of the permeability distributions that result.

Research and Educational Accomplishments

Specific accomplishments are as follows:

- (1) *Design and development of a lightweight syringe-based air minipermeameter (LSAMP).* One reason for the high cost of large numbers of hydraulic conductivity measurements is the large amount of labor and time involved in traditional measurements in which cores are taken in the field and returned to the laboratory for

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permeability measurement using water as the working fluid. In order to greatly reduce this investment of time and labor we designed and developed a lightweight field permeameter using air as the working fluid. This device weighs only 2 kg and can easily be carried to remote field locations. Measurements take only a few minutes. These characteristics enable hundreds of permeability measurements to be taken in the time formerly required for only one or two. The design of the LSAMP was published in *Ground Water* by Davis et al. (1994). The design was quite successful and has since been widely used in numerous hydrogeological investigations.

- (2) *Coarse-scale hydrogeological mapping and permeability measurement of an alluvial aquifer study site.* The alluvial architecture of a 0.16 km² area of the Sierra Ladrones Formation at Bosque in the central Rio Grande Valley, New Mexico, was mapped in detail and a large number of permeability measurements were performed on the same sediments, using the LSAMP. The site mapped was a "peninsula" projecting forward from an escarpment and thus the units could be mapped in three dimensions. Both the spatial distribution of the elements and the permeability measurements were analyzed using geostatistics. These data were published in Davis et al. (1993).
- (3) *Fine-scale mapping and permeability measurement.* Three different sites were investigated by mapping and permeability measurement at the meter scale (rather than km scale, as in (2), above). The objective was to investigate the role of bounding surfaces between lithofacies in spatial distribution of permeability. These data were published in Davis et al. (1997).
- (4) *Graduate education.* Graduate education and training was one of the goals of the project. Three M.S. theses and one Ph.D. dissertation were produced based on research funded by the grant.

Research Findings

- (1) *Control of large-scale permeability distribution by architectural elements.* Statistical analysis of hundreds of LSAMP measurements verified that different alluvial architectural elements are characterized by differing permeability means and variances. Analysis of the three-dimensional geometry of the mapped architectural elements at the Bosque site using indicator kriging revealed a characteristic geostatistical structure, determined by the nature of the alluvial architecture. This type of sedimentological analysis can be used to advantage in future site characterization activities. These findings were published in Davis et al. (1993).
- (2) *Nature of permeability spatial variations.* Most geostatistically-based models for the spatial variation of permeability that were employed at the time the project began assumed that the permeability varied smoothly and could be described by a gaussian model. Our findings showed that this was only partially true. Within individual alluvial lithofacies, gaussian distributions were indeed found. However, at the level of contacts between different lithofacies or elements, the spatial variation of permeability was generally abrupt and was controlled by the three-dimensional geometry of the lithofacies or elements rather than by any classical geostatistical

parameter. This is a result of fundamental significance for the conceptual nature of geostatistical models, and was published in Davis et al. (1997).

- (3) *Relationship between fluvial bounding surfaces and the permeability correlation structure.* The fine-scale hydrogeologic data ((3), above) were analyzed to determine controls on the permeability correlation structure. They showed that different lithofacies exhibited distinctively different permeability correlation structures, controlled by the nature of the depositional processes. Further, they indicated that the spatial characteristics could be adequately simulated by a hierarchical geostatistical model that relied on gaussian variations within lithofacies and abrupt variations across bounding surfaces. These findings were also published in Davis et al. (1997).
- (4) *Semi-Markov geostatistical model.* The findings described above imply that standard gaussian models are not adequate for reproducing actual fluvial permeability distributions. We therefore developed a new geostatistical model based on the semi-Markov process. This model is capable of reproducing both the continuous nature of permeability variation within lithofacies and the abrupt variations across bounding surfaces. It has been submitted for publication by Colarullo and Gutjahr (1998).

Theses and Publications Resulting from the Project

The following theses and publications are included with this completion report.

Theses

Lohmann, R.C. (1992) A sedimentological approach to hydrologic characterization: A detailed three-dimensional study of an outcrop of the Sierra Ladrones Formation, Albuquerque Basin: M.S. Ind. Study Report, New Mexico Institute of Mining and Technology, Hydrology Program, Socorro, 125 p.

Gotkowitz, M. (1993) A study of the relationship between permeability distributions and small scale sedimentary features in a fluvial formation: M.S. Ind. Study Report, New Mexico Institute of Mining and Technology, Hydrology Program, Socorro, 93 p.

Davis, J.M. (1994) A conceptual sedimentological-geostatistical model of aquifer heterogeneity based on outcrop studies: Ph.D. dissertation, New Mexico Institute of Mining and Technology, Socorro, 234 p.

Planert, C.S. (1995) Determination of hydraulic conductivities of low permeability materials in the Sierra Ladrones Formation, Albuquerque Basin: M.S. Ind. Study Report, New Mexico Institute of Mining and Technology, Socorro, 234 p.
90 p.

Publications

Lohmann, R.C.; Davis, J.M.; Love, D.W.; and Phillips, F.M. (1991) Hydrogeologic investigations of upper Sierra Ladrones Formation: *New Mexico Bureau of Mines and Mineral Resources Bulletin 137*, p. 164-166.

Davis, J.M.; Lohmann, R.C.; Phillips, F.M.; Wilson, J.L.; and Love D.W. (1993) Architecture of the Sierra Ladrones Formation, central New Mexico: Depositional controls on the permeability correlation structure: *Geological Society of America Bulletin* **105** 998-1007.

Davis, J.M.; Wilson, J.L.; and Phillips, F.M. (1994) A portable air-minipermeameter for rapid in situ field measurements: *Ground Water* **32** 258-266.

Davis, J.M.; Wilson, J.L.; Phillips, F.M.; and Gotkowitz, M.B. (1997) Relationship between fluvial bounding surfaces and the permeability correlation structure: *Water Resources Research* **33** 1843-1854.

Colarullo, S. and Gutjahr, A. (1998) Optimization of hydraulic conductivity measurement in multiple-scale geologic material: *Advances in Water Resources*, submitted. (not included with completion report)